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The potentials of the controllable rubber trailing edge flap (CRTEF)

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Abstract

The development of a controllable rubber trailing edge flap (CRTEF) for a wind turbine blade is presented in the paper. The flap can be deflected by controlling the pressure in suitable designed reinforced voids within the elastic flap. As the basic design is simple without any moving mechanical parts it is expected that a robust flap system can be achieved. A number of prototypes with a chord of 150 mm have been manufactured and tested showing a maximum deflection of +- 12 mm for a pressure of +- 8 bar. Six of these prototypes were glued together and mounted on a 1.9 m long airfoil section model with a chord of 1 m for test in a wind tunnel. A maximum delta C_L of about 0.2 was measured in the wind tunnel tests and a time constant around 80 ms. The potential load reduction on a MW turbine is presented based on aeroelastic simulations and using the wind tunnel test results of the flap characteristics.

Introduction

A number of numerical studies within the last 5-8 years have shown a big potential for reduction of the dynamic loads on wind turbines by using distributed control surfaces on the blades, see e.g. the overview presented by Barlas and van Kuik [1]. In a recent study Andersen et al. [2] computed a reduction of flapwise fatigue loads of 37% on the 5 MW reference wind turbine at operation in turbulent wind at a mean wind speed around rated power when three tailing edge flaps, each with a length of 10% of radius were mounted. The flap control is typically combined with the common pitch control of the blades which then mainly controls the response due to the slow but big variations in the wind speed whereas the flaps will counteract the fast changes in loads due to turbulence.
Different types of control surfaces have been considered. Microtabs investigated by van Dam et al. [3] are small translational devices (comparable with a gurney flap) placed near the trailing edge which can be deployed a distance of 1-2% of the chord perpendicular to the airfoil surface and in this way change the flow direction at the trailing edge and thus also the lift. At Risø DTU the research has been focussed on the concept of variable trailing edge geometry. This means that the aft part of the airfoil is deformed smoothly ensuring a high aerodynamic performance and a low aeroacoustic noise.
The considerable research carried out on modelling the different variants of distributed controllable surfaces and evaluating their load alleviation potentials has not led to many specific technology solutions for implementations on wind turbines. However, an airfoil section with piezoelectric flaps was tested in a wind tunnel by Bak et al. [4] and Barlas and van Kuik [1]

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reports results from wind tunnel tests of a model rotor with two 90 cm long blades, a chord length of 12 cm and with a flap of 50% of chord length. The flaps were actuated with piezoelectric bender actuators.
Although some inspiration to the technology solutions for distributed control surfaces can be found within the helicopter research literature the differences between the two applications (wind turbine and helicopter) are considerable. The difference in size of blades is obvious but also e.g. the quite different conditions for service where a helicopter rotor can be inspected much more frequently than a wind turbine.
The lack of technology solutions for flap control for wind turbines initiated a development work at Risø DTU in 2006 with the main objective to develop a robust and efficient flap system for implementation on MW turbines. This led to the design of the controllable rubber trailing edge flap (CRTEF) and the present paper gives a short presentation of this development work and some test results on prototypes including wind tunnel test results for a 1.9 m long section with a chord of 1 m and a 15% flap. The performance measured on the prototypes is used as input for aeroelastic simulations on the 5MW reference wind turbine with flaps to evaluate the potentials of the CRTEF.

Development of the CRTEF

Design space and requirements

The influence of size and shape of the variable trailing edge geometry on the aerodynamic characteristics was investigated by Troldborg [5]. It was found that a flap size of 5-10% was optimal as concerns influence on lift and with minimal drag penalty. Another important parameter is the total time lag in the flap response which is composed of the time constant of the flap itself as well as different time constants in the control loop. This has also been investigated in different numerical studies and e.g. the study of Andersen et al. [2] shows that an additional delay of 100 ms in a flap control system for the 5 MW reference wind turbine can reduce the load alleviation potential by 20-50% depending on the specific flap configuration. Besides the design requirements on flap size and the flap response speed, flap robustness and system simplicity were other important parameters set up as frame for the development work.

The basic design

The initial design studies led to the basic concept of a trailing edge flap manufactured in an elastic material such as e.g. rubber or plastic and with suitable reinforced voids that can be

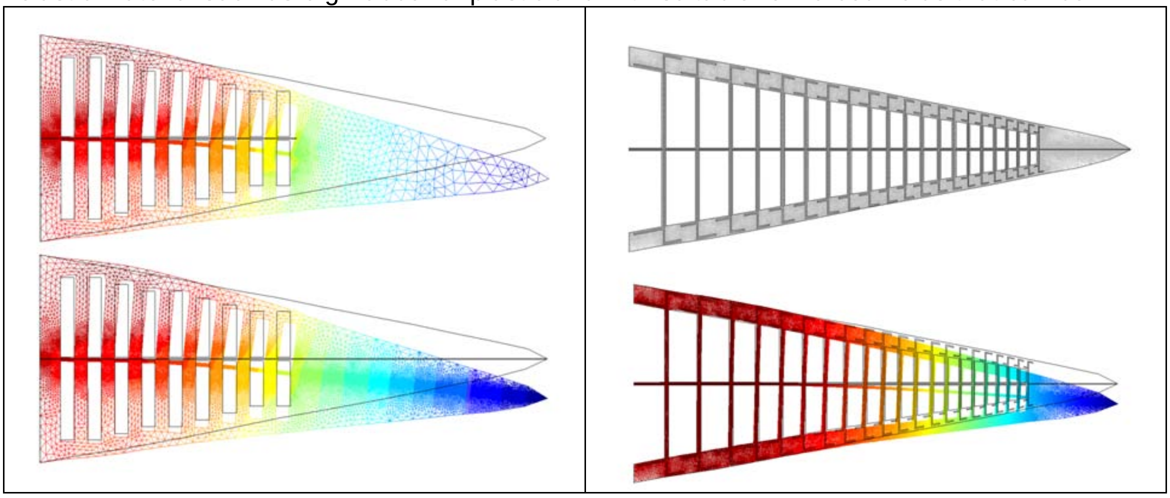

Figure 1 Two different void configurations modelled in 2D with the COMSOL software [6]. The figures show the deflection of the flap due to pressure in the upper row of voids.

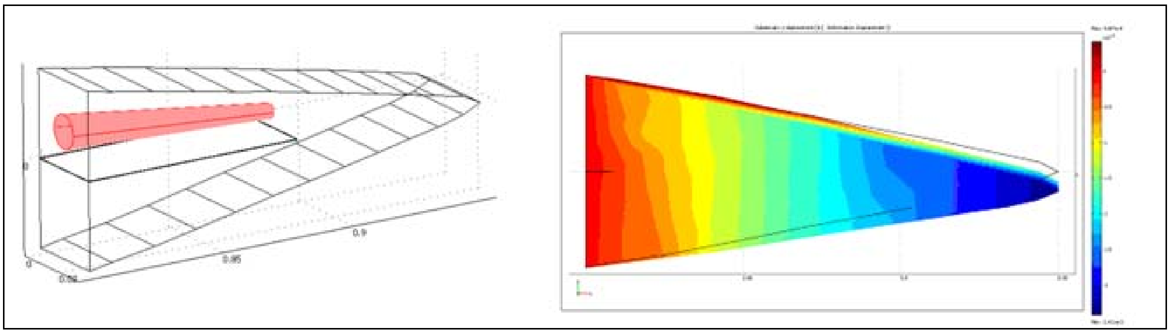

Figure 2 Conical voids in chordwise direction were modelled with a 3D COMSOL model.

pressurized with a medium such as air or a liquid and in this way give the desired deflection of the flap.

During the development of the flap concept the COMSOL [6] software was used to model several void layouts and two of the designs are shown in Figure 1 illustrating the deflection of the flap when the upper row of voids are pressurized. The design to the right in Figure 1 has metal parts inside the elastic material to control the deformation.

In Figure 2 a three-dimensional COMSOL model of a void in chordwise direction is shown. This design has big advantages in the manufacturing process compared with the design with voids in spanwise direction as the cores in the moulding process are much simpler and shorter.

The final design selected for building a prototype was therefore the design with conical, reinforced voids in chordwise direction.

Building and testing prototypes

Several prototypes with the same void arrangements but with different types of reinforcements of the voids such as carbon fibres or metal springs were manufactured in the Materials Research Division at Risø DTU, Figure 3.

Figure 3 Manufacturing of prototypes was carried out by the Material Research Division at Risø DTU. Different silicone rubber types were tested.

The flaps were manufactured in silicone rubber and in a size of 15 cm chord and 30 cm spanwise length suited for a NACA0015 airfoil section with a total chord of 1 m resulting in a flap relative percentage of 15%.

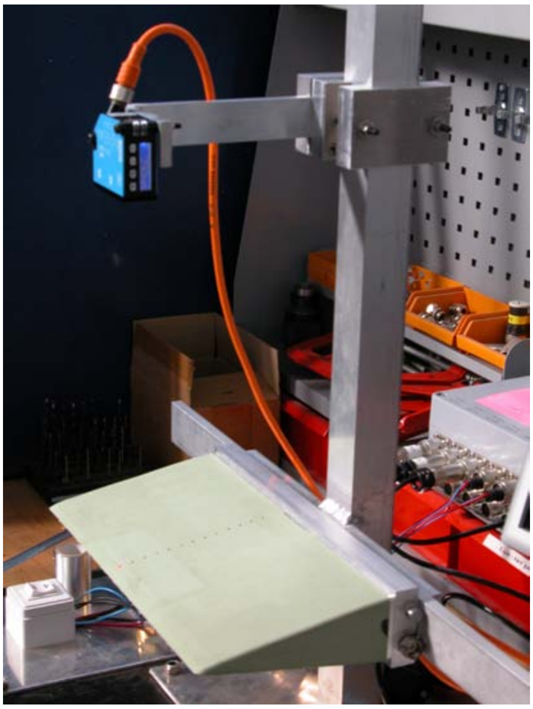

Figure 4 The prototypes were tested in a rig where the deflection at different chordwise positions and the applied pressure was measured.

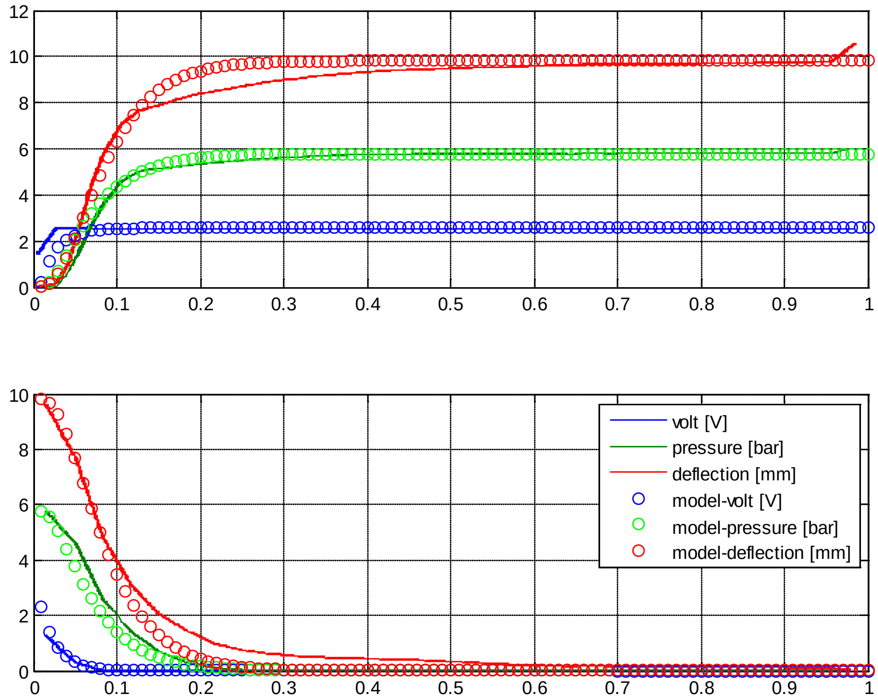

Figure 5 Upper part of figure.; step change with increasing pressure. Lower figure; step change with release of pressure.

The performance characteristics of the prototypes were derived from measurements in a test rig where the deflection of the flap and the applied pressure was sampled with a frequency of 35 Hz for manual actuated step changes in pressure, Figure 4. The dynamic response of the flap is an important characteristic of the flap for the capability of reducing aerodynamic loads. An indicial type model was used to characterize the dynamic response of the flap which later was used as input in the aeroelastic simulations. In Figure 5 the measured deflection and the modelled deflection is shown for a step change in both flap directions. It is apparent that the pressure and flap deflection correlates well. The first small step in volt at t=0.02s for the increasing pressure case, Figure 5 (top), could be a result of the low sampling rate.

Wind tunnel model and testing

In December 2009 the CRTEF prototype described above was tested in the VELUX wind tunnel which is of the closed return type with an open test section having a cross section of 7.5x7.5 m and a length of 10.5 m. The cross section of the quadratic jet blowing into the test section is 3.4x3.4 m. The maximum flow velocity is U=40 m/s giving a Reynolds number of 2.45×10^6 for the airfoil. A NACAA0015 airfoil section model with a chord of 1 m and a spanwise length of 1.9 m was manufactured and instrumented with 64 pressure taps. Six of the prototype flaps described above were glued together and mounted on the airfoil section model where 15% of the original trailing edge part of the model was cut away, Figure 6. The airfoil section model with the flap was afterwards mounted in a test rig 1.7 m from the tunnel floor and 3.2 m from the nozzle outlet as seen in Figure 7.

Figure 6 On a 1.9 m long NACA0015 airfoil section model with a chord length of 1 m, six of the flap prototypes were glued together and then attached to the airfoil section model.

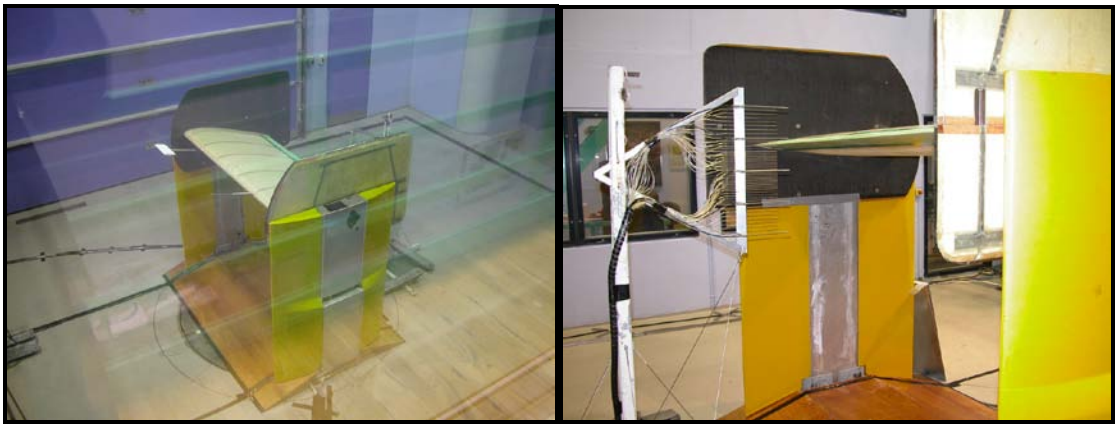

Figure 7 On the photo to the left the test rig with the 1.9m long test section is seen. The photo to the right shows the rig with pitot tubes for measuring the airfoil drag.

Pressure distributions were measured for a number of step activations of the flap at different mean angles of attack. The CRTEF was controlled using proportional pressure valves which could regulate the pressure from zero and up to nine bars. To access the aerodynamic response the pressure distribution was measured using 64 pressure taps drilled on the suction and pressure side of the airfoil. An example of the steady state measured pressure distributions for two flap deflections is shown in Figure 8 for an angle of attack α of 8 deg. and a flap angle β of 2.4 and -8.0 deg., respectively. Unfortunately, it was not possible to install pressure taps in the rubber material which would have enabled measurement of the full aerodynamic response including the pressure near the trailing edge.

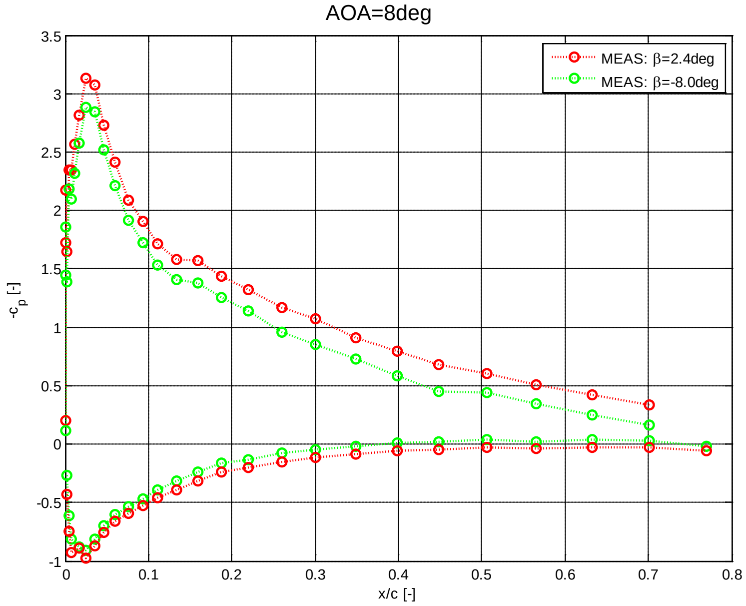

Figure 8 Steady pressure distribution for two flap positions.

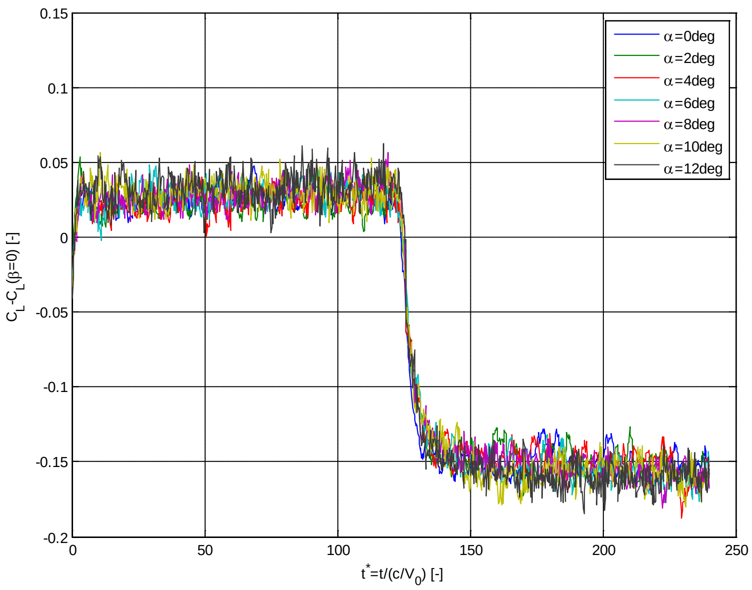

Figure 9 Aerodynamic response due to step changes in the flap for incidence angles from 0 to 12 degrees.

To evaluate the reproducibility numerous series of CRTEF step changes were carried out. Some of these measured aerodynamic responses are shown in Figure 13. The highest incidence angle is 12 degrees which is still at a point where the viscous effects play a minor role. A delta C_L of approximately 0.2 has been measured but due to a leakage in one of the voids this was mainly the response for a deflection to one side.

According to CFD calculations using a similar flap deflection, a delta C_L of 0.25 should have been obtained. Future wind tunnel campaigns will focus on having pressure taps near the trailing edge, which would give a higher accuracy of C_L and C_M. Figure 13 illustrates a high level of reproducibility for the measured time series and the derived time constant is approximately 80 ms.

Two different inflow sensors tested

Two different inflow sensors were tested during the wind tunnel measurement campaigns. One sensor was a five hole pitot tube which measures the local inflow angle and the relative velocity. The other sensor was a small sensor airfoil mounted in front of the main airfoil section on a rod with a strain gauge giving a signal proportional to the lift on the small airfoil, Figure 10. The advantage of a sensor in front of the airfoil section is that the control signal of a disturbance such as a gust is available before (e.g. 15-20 ms) the gust hits the main blade section. For individual blade pitch control the use of inflow measurements from a five hole pitot tube has been demonstrated to be quite efficient, Larsen et al. [7]. However, in the present measurement campaign no control feedback system was implemented and the inflow sensors were mounted in order to test the quality of the signals for use in a control system

Figure 10 Two different inflow sensors were tested: a five hole pitot tube and a small sensor airfoil mounted on a rod with a strain gauge giving a signal proportional to the lift on the sensor airfoil.

Aeroelastic simulations

The potential load reduction using the CRTEF system on a MW turbine was simulated with the aeroelastic code HAWC2 [8] and using the flap characteristics measured during the wind tunnel tests. Different sensor types for providing the input signal to the control system were investigated in the simulations. This comprises the two sensors mentioned above; a five hole pitot tube and the robust and simple system based on measurements of the lift on a small sensor airfoil. However, also more common control signals such as strain gauge signals from different positions on the blades were used as well. The five MW reference turbine used in the UpWind project was also used in the present investigation. In the simulations the turbine is divided into substructures like tower, nacelle and blades using the multi-body code HAWC2. Each substructure has its own coordinate system which facilitates rotations of the substructures with respect to each other. The multi body elements use the Timoshenko beam elements with six degrees of freedom per node. Aerodynamic torque, thrust and other loads are dynamically calculated using an unsteady Blade Element Momentum (BEM) model approach with various unsteady wake effects. The structural properties of the wind turbine used for the aeroelastic calculations such as centre of gravity, elastic, shear and pitch axis is from Jonkman [9].

Aeroelastic results

The potential load reduction on the reference turbine presented here are based on aeroelastic simulations using the wind tunnel test results of the flap characteristics and a control algorithm with the strain at a distance r_s from the blade root Figure 11 as input. The flap is a continuous 18.9 meter long flap which corresponds to 30% of the overall blade length.

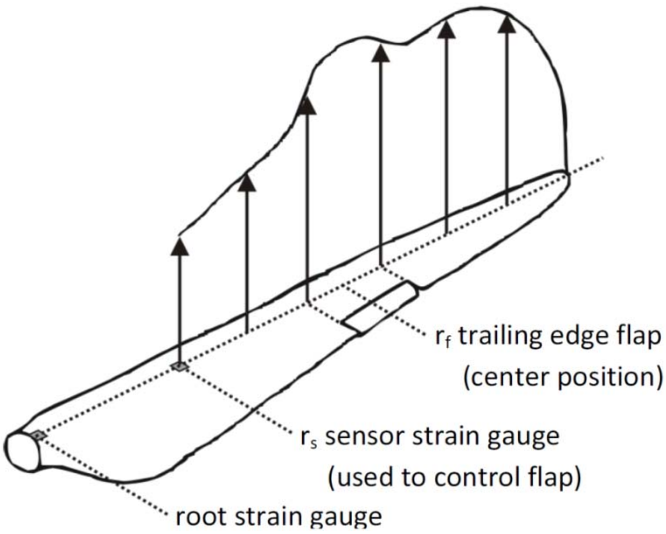

Figure 11 Sensor and control setup for aeroelastic simulations.

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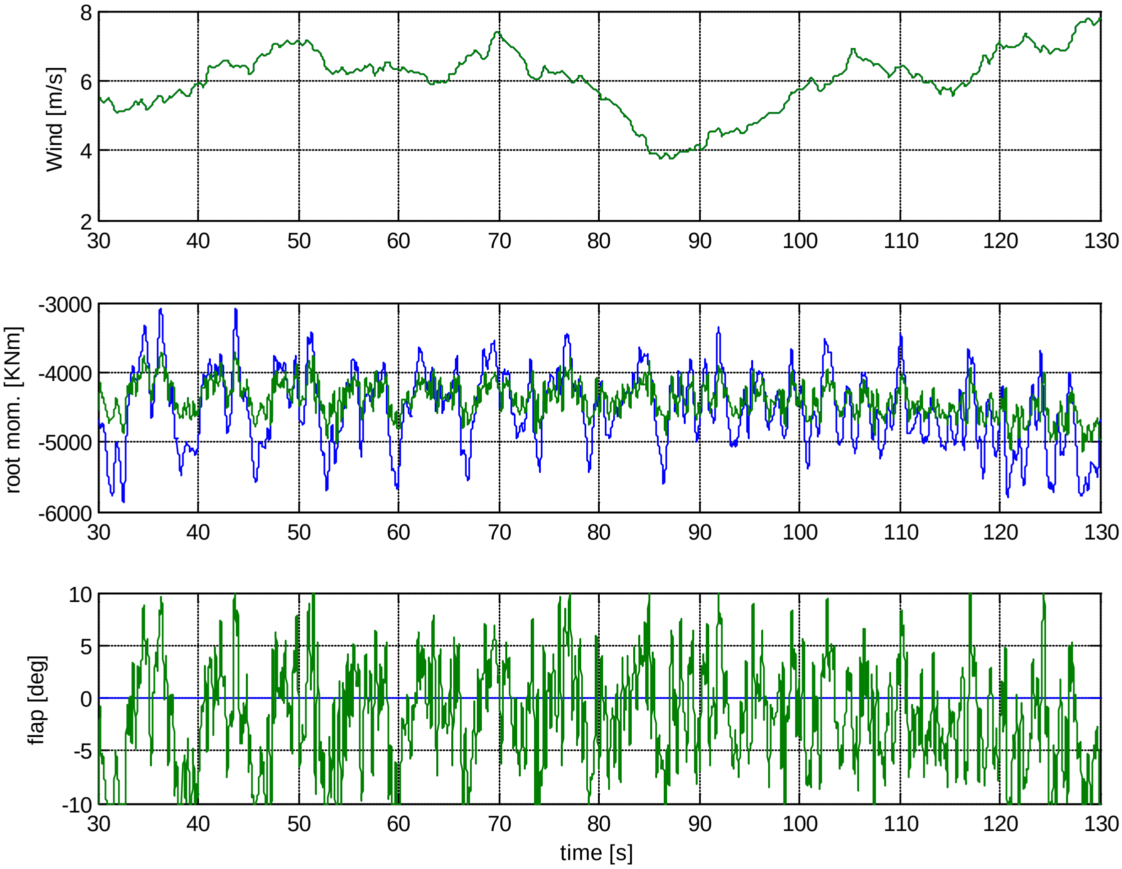

Figure 12 Simulations at 6m/s free wind speed. Blue line without flap control and green line with active flap.

The blade root strain gauge in Figure 11 shows where the forces are evaluated in the simulation. Extracts of simulated time series are shown in Figure 12 and Figure 13 for two different mean wind speeds. Notice how the flapwise blade root moment appears to fluctuate much less for the CRTEF controlled case compared to the uncontrolled case where the balance between generator moment and aerodynamic torque represents the only active control for the 5 MW reference turbine. The mean free wind speed is 6m/s for the simulation shown in Figure 12, whereas, a time series with 8m/s mean free wind speed is used in Figure 13.

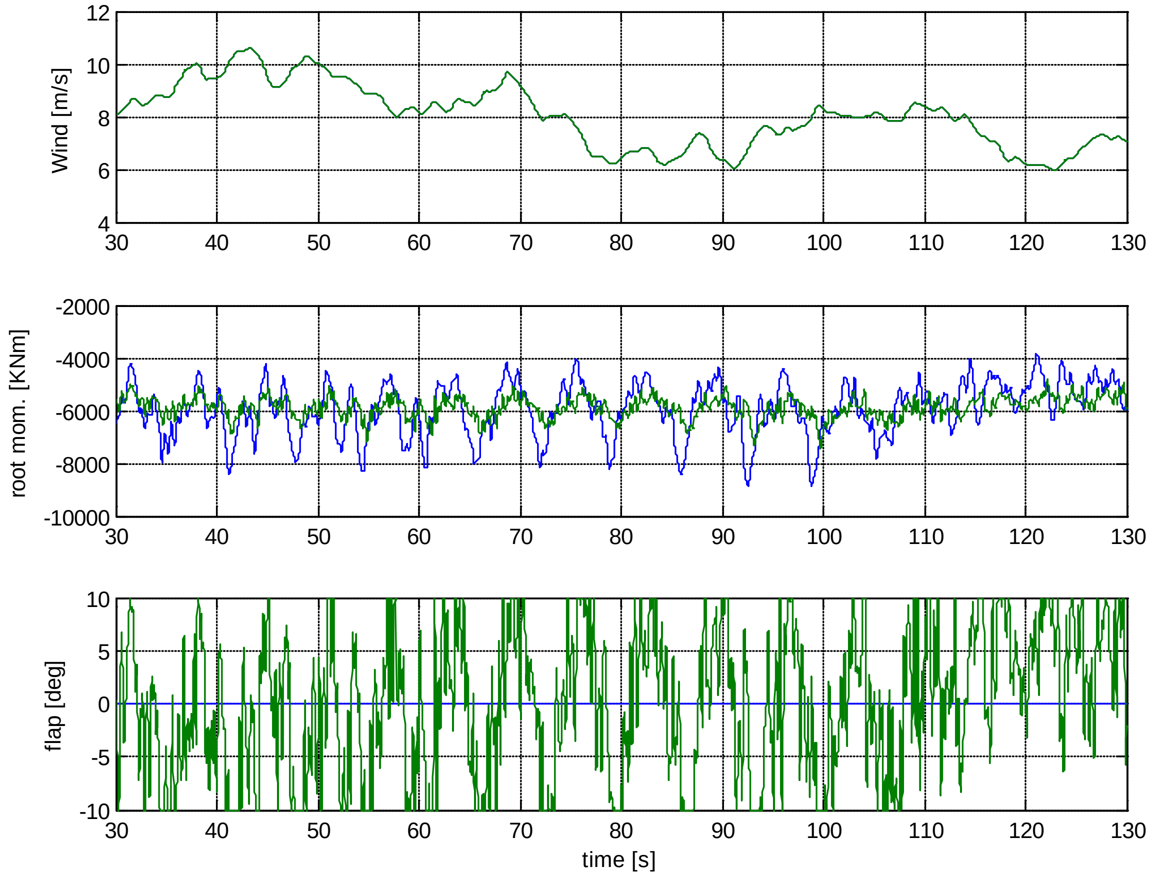

Figure 13 Simulations at 8m/s free wind speed. Blue line is without flap control and green line with active flap.

The equivalent fatigue load number is used to quantify the load reduction in percentage. For the CRTEF controlled case and the uncontrolled case in Figure 12 the equivalent flapwise blade root moment load is reduced from 1850kNm to 902kNm, which is 51% reduction. For the blade flapwise root moment, shown in Figure 13, the equivalent fatigue load number is reduced from 3370kNm to 1681kNm, which is 50% reduction.

Load reduction illustrated by PSD of flapwise moment

The influence of the flap control on the frequency content of the flapwise blade root moment is shown in in Figure 14. For a wide range of frequencies up to 4p there is a significant load reduction in the flapwise blade root moment. It should be noted that the present results are from simulations of a flap of 6.3 m length which is only 10% of radius.

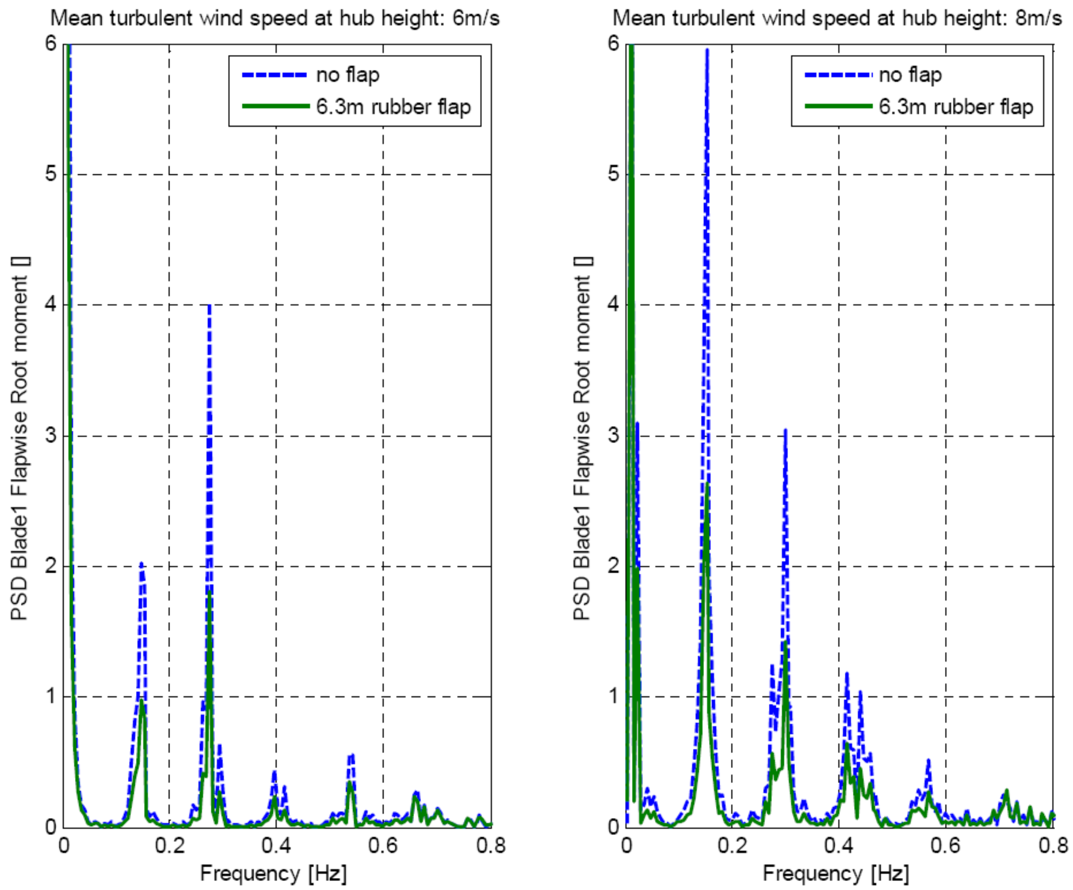

Figure 14 Power spectral density of the flapwise blade root moment; left 6m/s and right 8m/s.

Summary

We have developed a new flap design; the controllable rubber trailing edge flap (CRTEF) which can be deflected by controlling the pressure in suitable designed reinforced voids within the elastic flap. A number of prototypes with a chord of 150 mm have been manufactured and tested showing a maximum deflection of +- 12 mm for a pressure of +- 8 bar. Six of these prototypes were glued together and mounted on a 1.9 m long airfoil section model with a chord of 1 m. The measured total delta C_L was around 0.2 but this was mainly for a one sided deflection of the flap due to a leakage in one of the voids. It is thus expected that the present flap design can give a change in C_L of about+-0.2 for a pressure variation of +- 8 bar. The potential load reduction on a MW turbine is presented based on aeroelastic simulations and using the wind tunnel test results of the flap characteristics. The maximum load reduction obtained for several mean wind speeds are 50% for equivalent loads in the flapwise blade root moments.

Outlook

The CRTEF has now been developed to a stage where the functioning principle has been verified during different tests, latest in a wind tunnel experiment in 2009. A new development project has been formulated which will bring the present CRTEF technology up to a stage where it will be ready for installation as a prototype on a full scale MW turbine and the time frame is 2-3 years. It is expected that optimizing the design can result in a 50% increase in flap deflection as well as a considerable increase in bandwidth. In this new development project industrial partners will be involved so that e.g. manufacturing aspects and integration of the flap in the blade structural design will be considered.

Acknowledgement

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